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Individual differences in change blindness are predicted by the strength and stability of visual representations

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Abstract

The phenomenon of change blindness reveals that people are surprisingly poor at detecting unexpected visual changes; however, research on individual differences in detection ability is scarce. Predictive processing accounts of visual perception suggest that better change detection may be linked to assigning greater weight to prediction error signals, as indexed by an increased alternation rate in perceptual rivalry or greater sensitivity to low-level visual signals. Alternatively, superior detection ability may be associated with robust visual predictions against which sensory changes can be more effectively registered, suggesting an association with high-level mechanisms of visual short-term memory (VSTM) and attention. We administered a battery of 10 measures to explore these predictions and to determine, for the first time, the test–retest reliability of commonly used change detection measures. Change detection performance was stable over time and generalized from displays of static scenes to video clips. An exploratory factor analysis revealed two factors explaining performance across the battery, that we identify as *visual stability* (loading on change detection, attention measures, VSTM and perceptual rivalry) and *visual ability* (loading on iconic memory, temporal order judgments and contrast sensitivity). These results highlight the importance of strong, stable representations and the ability to resist distraction, in order to successfully incorporate unexpected changes into the contents of visual awareness.

Key words: individual differences; change blindness; attention; perceptual rivalry; predictive processing

Introduction

Change blindness (CB) is a striking phenomenon that contradicts our intuitions about possessing rich and detailed representations of our visual world and highlights the limitations of the top-down and bottom-up neurocognitive mechanisms underlying subjective visual awareness. Long-standing behavioural research on CB has established that people tend to be surprisingly

poor at noticing sudden, unexpected changes in the visual environment, whether the changes occur in static displays of visual scenes (Rensink *et al.* 1997; Simons and Rensink 2005), dynamic motion pictures (Levin and Simons 2000), or in real world settings (Simons and Levin 1998). A common technique for inducing CB is to introduce a visual transient between the pre-change and post-change scenes, such as a flicker or ‘mudsplash’ in static displays (Rensink 2000; O’Regan *et al.* 1999), camera pans

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Highlights

- Measures test-retest reliabilities of commonly used change detection and attentional tasks.
- Demonstrates that change detection performance is stable and generalizes across different paradigms.
- Shows superior change detection is predicted by the strength and stability of visual representations.
- Contributes to the understanding of change detection within the predictive processing framework.

or cuts in dynamic video clips (Levin and Simons 1997; Smith and Milne 2009), or presenting the change across saccades (Grimes 1996). It is argued that when a visual transient is introduced, the bottom-up signal of the change is masked by the interference, which disrupts exogenous orienting to the change (Rensink et al. 1997; Beck et al. 2006). This in turn is thought to impair encoding of the change into visual short-term memory (VSTM) and to bias the visual system towards an endogenous, effortful visual search for the change. Change detection is improved with cueing, expectations of change, relevance to current task goals and for contextually central and socially relevant stimuli (Simons 2000; Simons and Rensink 2005; Ro et al. 2001). Despite decades of research, little is known about individual differences in the ability to detect visual changes. In this study we explored, for the first time, whether people reliably differ in their ability to notice changes in naturalistic scenes. Furthermore, we examined using a predictive processing framework whether change detection is predicted by inter-individual variability in the selection and maintenance of visual information (attention and visual memory) or perceptual sensitivity (detection and discrimination of simple stimuli).

The theoretical framework of predictive processing (Rao and Ballard 1999; Friston 2010; Hohwy 2013; Clark 2013, 2015) considers the human brain as a hierarchically organized hypothesis-testing system that engages in predictive inference about the environmental causes of sensory input. Visual perception emerges from recurrent, bottom-up and top-down interactions in visual pathways (Hohwy et al. 2008). Discrepancies between the prediction (i.e. the most likely interpretation of the visual input) and afferent sensory data generate prediction error signals that flow in the bottom-up direction in the visual hierarchy to update the current prediction. Crucially, the system perpetually strives to minimize prediction error to accomplish behaviourally optimal visual inferences. In this theoretical framework, CB could arise from a failure to update the current prediction of the state of the visual world. This in turn could occur due to a variety of reasons within this framework; the prediction error generated by the change may be too weak or imprecise to create a shift in awareness, the representation of the pre-change scene could be too weak or imprecise to consciously register a deviation from it, or it could be a combination of both processes. For example, a weaker representation could engender a less precise prediction error. There is some evidence that missed changes are still processed at some level in the visual system, given above chance recognition performance on forced-choice memory tests with undetected items (Hollingworth and Henderson 2002). This suggests the prediction error signal generated by the change is transmitted but does not reorganize the contents of awareness due to some limitation in the interactions of predictive and corrective mechanisms of visual inference. By adopting an individual differences approach to the phenomenon of CB, our aim is to reveal the predictive processing mechanisms that support superior change detection.

We adjudicate between two broad, albeit not mutually exclusive, theoretical possibilities as to why some individuals may be

better than others at noticing change. On the one hand, superior change detection may be reliant on forming robust, stable and accurate predictions about the visual world. This is in line with existing research demonstrating that CB arises in some part due to impaired encoding and maintenance of scene representations in VSTM. For example, disruption of a VSTM-associated region in parietal cortex with transcranial magnetic stimulation (TMS) during the presentation of pre-change scene leads to greater CB than post-change (Tseng et al. 2010), suggesting having a good representation of the scene prior to change is crucial. Furthermore, being able to resist distraction by visual transients and successfully allocate top-down attention in accordance with VSTM representations is likely to support faster detection: exogenous orienting to changes in the CB task is disrupted by visual transients and is overcome by engaging in endogenous visual search (Beck et al. 2006). Consequently, it can be hypothesized that higher VSTM accuracy, lower susceptibility to attentional capture and lower distractibility will predict superior change detection.

An alternative hypothesis is that visual change detection is enhanced by a tendency to assign a greater weight to low-level sensory signal. This would boost the strength of prediction error that is transmitted up the visual hierarchy to correct perceptual inferences. Greater perceptual sensitivity, quantified by such psychophysical measures as temporal order judgement (TOJ) and contrast sensitivity, have been shown to predict performance on a range of different visual tasks, including visual search (Ward et al. 2016), so could potentially also support change detection. Similarly, the alternation rate in perceptual rivalry paradigms, where individuals are faced with a constant but ambiguous stimulus (e.g. a Necker cube) and subjectively perceive two alternating visual interpretations, has been argued to reflect this kind of bias towards assigning more weight to sensory evidence. Specifically, Kanai et al. (2011) posit that individuals who subjectively experience a faster alternation rate when viewing bistable stimuli assign greater weight to sensory prediction error, and thus update their visual inferences faster. Inter-individual differences in various types of perceptual rivalry are large and have high test-retest reliabilities (Miller et al. 2009), which suggests an intriguing possibility that they index a general predictive processing bias which could manifest in other visual abilities including change detection. If this low-level sensitivity hypothesis is correct, we expect a high alternation rate in perceptual rivalry, high-contrast sensitivity and a low threshold for TOJs to predict superior change detection. This interpretation is intuitively appealing, as we expect sensitivity to minute differences in signal to be associated with having a more detailed representation of the visual world.

In summary, the main focus of present research was to determine whether it is the strength of high-level cognitive capacities or low-level perceptual sensitivity (or both) that supports the formation of accurate and behaviourally optimal moment-to-moment representations of the visual world. All tasks involve some low-level element (given that they all involve visual stimuli) and a high-level element (minimally the task

instructions), but the theoretically interesting question is where in this hierarchy lies the bottleneck that determines individual differences in performance (and there may be multiple bottlenecks). The assumption made here is that the bottleneck in tasks such as VSTM and avoiding distraction is at the level of later 'high level' visual processes (involved in selection and maintenance of visual information) but that the bottleneck in tasks involving discrimination of weak visual signals lies in early 'low level' visual processes (involved in simple detection of visual information). In addition, we consider that the two alternative hypotheses may be related; possessing robust representations may enable the individual to generate more precise prediction errors, which may boost conscious detection of visual change. In this case, we would expect both attentional and memory measures, and perceptual sensitivity measures to predict detection performance.

To explore these hypotheses, we administered a battery of 10 different tasks, some of which we presented over two sessions to determine their test-retest reliabilities. We employed two measures of change detection; the commonly used 'flicker' CB paradigm with naturalistic scenes and short video clips containing continuity errors. To measure the strength of high-level representations, we included a VSTM task assessing three sub-components of VSTM (iconic, fragile and robust) that reflect early versus later memory processes and differ in their capacity and proneness to be over-written (Sligte et al. 2008, 2009). To assess the ability to exert top-down control in the presence of distractors, we administered an attentional capture task and the Cognitive Failures Questionnaire (Broadbent et al. 1982), which assesses self-report distractibility. We used two psychophysical measures of sensitivity to low-level visual signal; temporal order judgment threshold and contrast sensitivity. Additionally, we included a perceptual rivalry task involving an ambiguous structure-from-motion sphere in order to measure the tendency to update visual predictions in light of conflicting input (Kanai et al. 2011); high alternation rate may indicate assigning greater weight to prediction error (a low-level bottleneck) whereas a low alternation rate may reflect greater stability of perceptual predictions (a high-level bottleneck).

Collectively, these eight tests were motivated by the theoretical framework outlined above. In addition, we included two tests that are more exploratory in nature; the Vividness of Visual Imagery Questionnaire (Marks 1995), and a test measuring a visual pattern recognition aspect of general intelligence (Condon and Revelle 2014). Our approach was to (i) focus on the small number of correlations that were hypothesized *a priori* and that clearly address the two proposed hypotheses (ii) regard other correlations as exploratory, in which the effect size and direction of correlation is noted in order to make predictions for confirmatory research (McBee and Field 2017) and (iii) conduct a factor analysis of all the measures. The latter is important because it enabled us to take a holistic view of the dataset in a single analysis and identify which perceptual and cognitive abilities are associated with the tendency to notice visual changes.

Method

Participants

Sixty-three adult participants (Aged 18–38, Mean = 20.46, SD = 4.16; 54 female) with normal or corrected-to-normal vision and no reported colour vision deficiencies took part in this study. The participants were undergraduate students at the University

Table 1. Summary statistics of the following measures: CB parameter β , % of correctly identified changes in continuity error videos, attentional capture in ms, iconic, fragile and robust VSTM % accuracy, number of alternations in perceptual rivalry, TOJ threshold in ms, CS parameters γ_{\max} , f_{\max} , β , and δ , CFQ distractibility score, VVIQ score and matrix reasoning task % accuracy. The final three columns indicate the Pearson test-retest correlation between the Session 1 and Session 2 scores of each test, together with the associated *N*, lower and upper 95% bootstrapped confidence intervals and significance values (2-tailed), respectively

Measure	N	Mean	SD	<i>r</i> (N)	95% CI	P-value
CB β	62	-5.27	1.15	0.45 (59)	0.20, 0.65	<0.001
CE % correct	63	48.51	12.07	0.02 (60)	-0.21, 0.29	0.865
Att. capture	63	59.89	36.98	0.50 (60)	0.29, 0.66	<0.001
VSTM Iconic	63	85.01	9.35	0.76 (60)	0.64, 0.86	<0.001
VSTM Fragile	63	74.69	10.25	0.72 (60)	0.58, 0.82	<0.001
VSTM Robust	63	62.86	8.55	0.54 (60)	0.31, 0.70	<0.001
Perceptual rivalry	62	37.77	16.18	0.58 (58)	0.28, 0.85	<0.001
TOJ	63	51.50	21.61			
CS γ_{\max}	54	1.46	0.28			
CS f_{\max}	54	0.37	0.15			
CS β	54	0.45	0.10			
CS δ	54	-0.45	0.21			
CFQ	63	21.86	4.44			
VVIQ	63	120.37	18.60			
Matrix	61	63.04	20.25			

of Sussex who received course credit and adults from the Brighton community who were reimbursed in cash. The study consisted of a battery of 10 perceptual and cognitive measures and comprised two separate sessions. All 63 participants completed the initial testing session (2 h), and 60 participants returned to the lab 1–4 weeks later to complete the final re-test session (1 h). Due to time constraints and technical issues a few participants did not complete all of the tasks in Session 1; appropriate *N* values are provided in Table 1. The study was approved by the Science and Technology Cross-Schools Research Ethics Committee (C-REC), at the University of Sussex.

Design

The test battery consisted of 10 different tasks; two different change detection tasks [CB task and continuity error (CE) detection task], a VSTM task, an attentional capture task, a perceptual rivalry task, two basic psychophysical measures [temporal order judgment (TOJ) and contrast sensitivity (CS) tasks], a questionnaire to assess self-reported distractibility [Cognitive Failures Questionnaire (CFQ), Broadbent et al. 1982], a questionnaire assessing the vividness of mental imagery [Vividness of Visual Imagery Questionnaire (VVIQ), Marks 1995] and a test of general intelligence (matrix reasoning task, Condon and Revelle 2014). All of the tasks were presented in Session 1 but only the CB, CE, attentional capture, VSTM and perceptual rivalry tasks were presented in Session 2 to determine their test-retest reliabilities. Figure 1 provides an illustration of the trial structure of each task. More information regarding stimulus viewing parameters is provided in Table 1.1 in Supplementary Materials.

Change blindness task

The CB task was adapted from the landmark study by Rensink et al. (1997) and required participants to find changing objects within flickering natural indoor scenes. Sixty image pairs were obtained from a CB database (Sareen et al. 2016); one image was

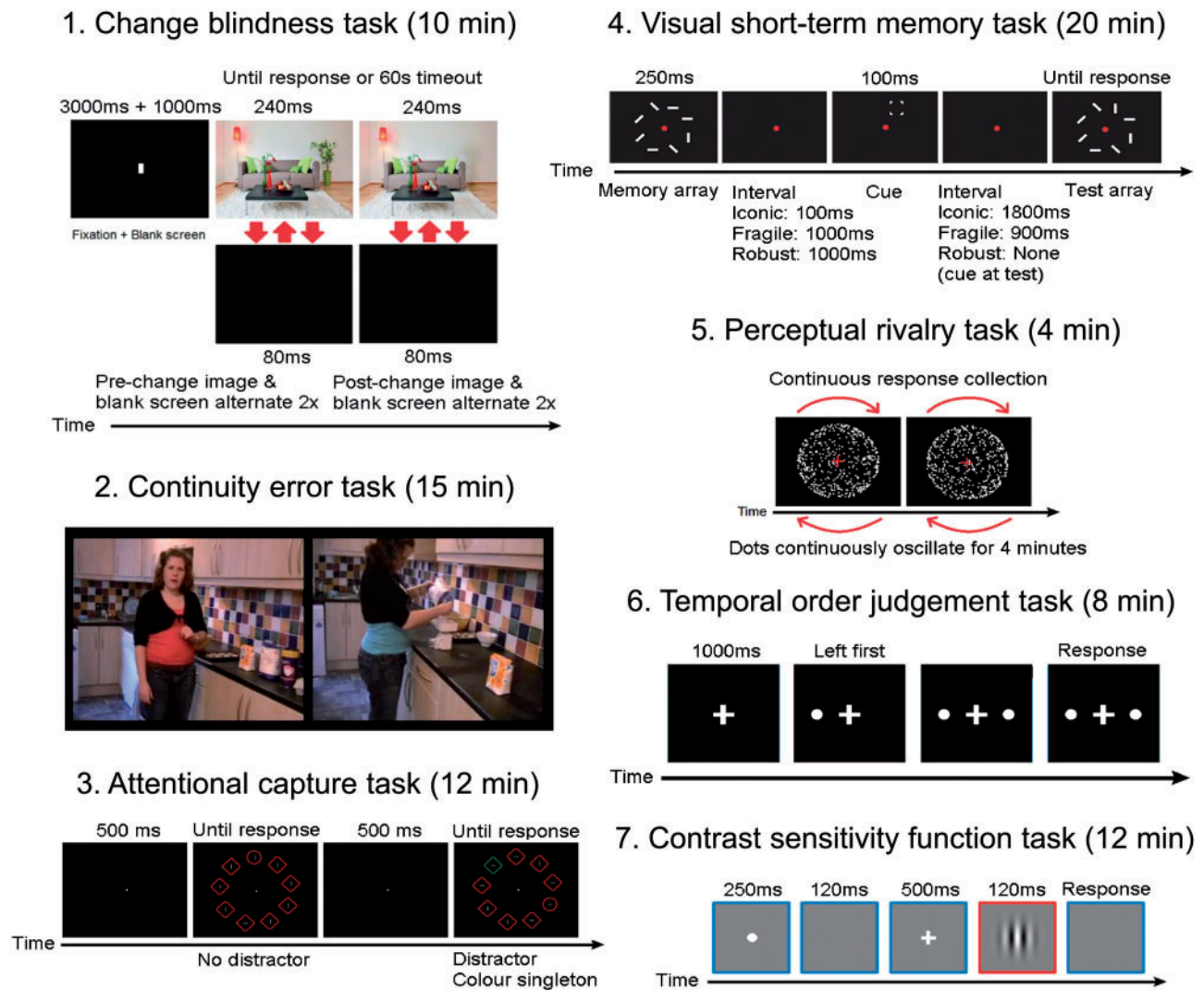


Figure 1. The stimuli and trial structure of the tasks in order of presentation. In the change blindness task, (1) the flickering cycle of pre-change scene, post-change scene and blank screen alternated for 60 s (if no response was given): the task was to click on the change. In the continuity error task, (2) the task was to describe any unexpected changes in video clips (e.g. the top of the actor changes colour). In the attentional capture task, (3) participants reported the orientation of the line inside the circle whilst ignoring the diamonds. In the VSTM task, (4) participants reported if the cued rectangle in the test array was the same or different as in the memory array; the time interval before and after the cue varied depending on condition. In the perceptual rivalry task, (5) participants clicked the mouse any time they subjectively perceived the ambiguous structure-from-motion sphere to change the direction of rotation. In the temporal order judgement task, (6) the objective was to determine which of the dots appeared first. In the contrast sensitivity task, (7) participants had to report if they saw a Gabor patch before or after the fixation cross.

an original indoor scene and in the other image one of the objects (e.g. a vase) was removed. Half of the object changes occurred on the left side of the image and half occurred on the right. The task was presented using Inquisit Millisecond software and consisted of one practice trial and 30 randomly intermixed experimental trials. On each trial the pre-change and post-change scenes alternated with a blank screen in between the two, creating a flickering cycle of image presentations lasting 60 s. Participants were instructed to use a mouse to click on the object that keeps appearing and disappearing. The next trial began after the mouse click or, in the case of no response, when the image cycle finished (after 60 s). There was an inter-trial interval of 1000 ms and a black screen with white fixation square was presented for 3000 ms before each trial. Different image pairs were presented in Sessions 1 and 2. To separate correct

from incorrect responses, regions of interest (ROIs) within each image were defined around the centre coordinates of the changed object (mean radius = 1°) and mouse clicks with coordinates outside ROIs (mean radius = 2°) were labelled as misses.

Continuity error detection task

In this task participants viewed short video clips, originally used by Smith and Milne (2009), containing continuity errors. The clips were spliced from a 20-min film on the topic of baking; during this film, an actor goes through each step of the recipe and gives instructions, whilst occasionally unexpected changes are introduced across cuts or pans in the camera angle. This task was presented using Inquisit Millisecond software, and participants viewed 10 clips that lasted on average 51 s; eight clips contained one continuity error and two contained none.

The continuity errors involved sudden changes to central-actor, central-object, marginal-actor, or marginal-object related aspects of the scene, with equal numbers of each change type. After watching each clip, participants were presented with two general questions about the baking instructions to gauge their level of attentiveness and were asked to describe any continuity errors in the text box provided. Different video clips were presented in Sessions 1 and 2.

Attentional capture task

The attentional capture task was similar to that described by Kanai et al. (2011). This task was presented using E-prime software and measures the extent to which participants are distracted by salient task-irrelevant stimuli. The task consisted of 12 practice trials and 300 experimental trials (4 blocks). A colour singleton distractor was present on 140 of the trials and absent on 148 trials. On each trial participants were presented with 9 shapes: 8 diamonds and 1 circle. Each shape contained either a horizontal or a vertical line—this was assigned randomly. The colour of the shapes varied; when no colour singleton was present all shapes were either green or red, whereas when a colour singleton was present all shapes were either green or red but one diamond was the opposite colour. Participants were instructed to report the orientation of the line inside the circle (e.g. horizontal or vertical) by keyboard responses as quickly and accurately as possible, whilst trying to ignore the diamonds. Attentional capture was estimated by subtracting the average correct response times (RTs) in the condition with no distractor from the condition with the distracting colour singleton.

Visual short-term memory task

The VSTM task measured three different VSTM processes; iconic, fragile and robust VSTM. In this task, adapted from Sligte et al. (2008, 2009), participants detected changes in the orientation of cued rectangles. The VSTM task was presented using MATLAB (Mathworks Inc.) and Psychtoolbox (Brainard 1997) and consisted of 288 trials (48 trials \times 6 blocks); the initial block was treated as practice. There were three types of trials with different cue onset times and after-cue intervals. In the iconic VSTM condition, a cue was presented 100 ms after the off-set of the memory array followed by an 1800 ms blank interval, targeting iconic VSTM store which has an unlimited capacity and largely relies on after-image. In the fragile VSTM condition, a cue was presented 1000 ms after the off-set of the memory array followed by 900 ms blank interval; this was designed to target fragile VSTM store thought to be relatively high capacity but prone to over-writing. In the robust VSTM condition a cue was presented 1000 ms after the off-set of memory array simultaneously with the test array appearing on the screen; this was designed to target robust VSTM store thought to store about four items. Each of these trial types was presented 96 times randomly intermixed. The test array included the words 'same' and 'different' in the top right and left corners of the screen, respectively. This prompted participants to click the right mouse button if the orientation of the cued rectangle in the test array matched its orientation in the memory array and the left mouse button if it did not. During the inter-trial interval (1600 ms) participants saw a green fixation point after a correct response and a red 'Error!' feedback after an incorrect response. Participants were instructed to respond as accurately as possible without prioritizing speed. The measure of interest was accuracy in each of the three cue conditions.

Perceptual rivalry task

The stimulus used in this task was the ambiguous structure-from-motion rotating sphere described by Kanai et al. (2010). It was presented using MATLAB and Psychtoolbox (Brainard 1997) and is typically experienced as an ambiguous sphere that appears to rotate either to the left or right, with the perceived direction of rotation alternating. The sphere consisted of 200 white dots moving sinusoidally with a red fixation cross in the middle and was presented against a black background. The sphere was continuously presented on the screen for two blocks of 2 min and participants had to respond by clicking the mouse whenever the sphere appeared to switch its direction of rotation. The measure derived was the total count of the reported perceptual alternations over the 4-min presentation of the sphere.

Temporal order judgement task

In this task taken from Ward et al. (2016), participants were presented with two adjacent stimuli in rapid succession using MATLAB and Psychtoolbox (Brainard 1997) and were asked to indicate which stimulus was presented first. The stimuli consisted of two white discs presented side-by-side against a black background. Participants were required to make keyboard responses to indicate whether the left or the right stimulus appeared first. The discs remained on the screen until the participant made a response. The inter-trial interval was 500 ms. A staircase procedure was used, where the initial difference between the onsets of the two discs was 35.29 ms, and this value was then adjusted in steps of 11.76 ms determined by the monitor's refresh rate. The onset difference was reduced after three successively correct trials and increased after every incorrect trial. Each change in onset difference represented a reversal, and ten reversals were required before the termination of the task. The measure of interest was the TOJ threshold time, which was calculated as the mean of the last ten onset differences (in ms).

Quick contrast sensitivity function task

The quick contrast sensitivity function is a test of sensitivity to contrast as a function of spatial frequency (Hou et al. 2010; Lesmes et al. 2010), taken from Ward et al. (2016). Participants had to detect Gabor patches using a two-interval forced choice paradigm. Participants were asked to press one of two keys to indicate whether a Gabor patch appeared before or after a fixation cross; they had 2 s after the offset of the stimulus to respond. The task was presented using MATLAB and Psychtoolbox (Brainard 1997) and consisted of 100 test trials. The estimated measures were four parameters of contrast sensitivity as a function of spatial frequency; these consisted of peak sensitivity (γ_{\max}), peak spatial frequency (f_{\max}), bandwidth (β) or the contrast sensitivity function's full width at half-maximum and truncation level or reduced gain at low spatial frequencies (δ).

Vividness of visual imagery questionnaire

This questionnaire by Marks (1995) assesses the extent to which people can vividly imagine visual scenes. Participants were presented with a description of a visual scene and then prompted to imagine the scene with their eyes closed. The vividness of the imagined scene was then assessed on 5-point scales ranging from 'No image at all' to 'Perfectly clear and vivid as if I was actually seeing it'. The questionnaire took 10 mins to complete, consisted of 32 separate questions in two blocks of 16 and was presented using Inquisit Millisecond software. The obtained value was the total vividness score.

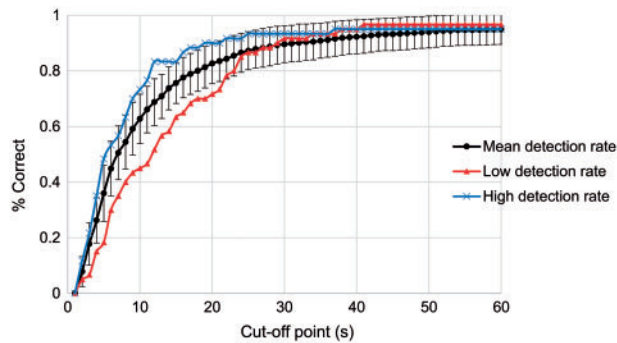


Figure 2. This graph illustrates the mean cumulative % correct in the CB task at different time points along with standard deviation error bars and the cumulative % correct for the highest and lowest performing participants in terms of the β value.

Self-reported distractibility

Self-reported distractibility was assessed with the CFQ designed by Broadbent et al. (1982), which involves various questions regarding everyday blunders and failures of attention and memory. The questionnaire took about 5 min to complete. Several lines of research have shown that CFQ consists of separate, albeit related, underlying factors; these often differentiate between questions pertaining to distractibility versus forgetfulness (Wallace et al. 2002; Rast et al. 2009). Therefore, only the total scores of questions that are a part of the distractibility factor identified by Wallace et al. (2002) were analysed.

Matrix reasoning task

An estimate of general intelligence (g) was obtained by assessing performance in a visual shape matrix reasoning task. This task consisted of 11 progressive matrices obtained via the Cambridge ICAR database (Condon and Revelle 2014), and these were presented as a paper and pen questionnaire in order of difficulty, with a time-limit of 15 min. It has been established that much shorter versions of progressive matrices with as few as 12 questions can have acceptable psychometric properties and predictive power (Bors and Stokes 1998; Hamel and Schmittmann 2006). Therefore, a short version of matrix reasoning task was justified for the purposes of this study. The percentage of correct responses was calculated.

Procedure

All participants signed informed consent. The initial session lasted 2 h, consisted of 10 different tasks and participants could take breaks in between the tasks. The task order in Session 1 was fixed for every participant: CB task, CE task, attentional capture task, VSTM task, perceptual rivalry task, TOJ task, CS task, VVIQ, CFQ and matrix reasoning task. Session 2 lasted 1 h, and again the task order was fixed: CB task, CE task, attentional capture task, VSTM task and perceptual rivalry task. A fixed order of tasks was used for all participants to maximize the differences between individual performances when all other variables are held constant (as recommended by Mollon et al. 2017). The initial two change detection tasks in both sessions, as well as the last three questionnaires from Session 1 were completed seated comfortably 57 cm from the computer screen (screen resolution = 1920×1080) with the light on in the room, whereas the remaining tasks in both sessions were completed seated 100 cm from a CRT monitor (screen resolution = 1280×1024) in a dark room with participants' heads resting on a chinrest.

Results

Data preparation

For the CB task the coordinates of the reported change locations were analysed and responses with coordinates outside the ROI were considered a failure to detect the change and added to misses. The cumulative percentage of correctly identified changes was calculated at each time point (e.g. percentage correct with RTs of below 1 s, 2 s, 3 s ... 60 s; see Figure 2 for an illustration). An inverse exponential function ($Y = \alpha e^{\beta/X}$) was then fit to this data, where Y is the cumulative percentage correct, X is the time in seconds, α is the asymptote and β relates to steepness/curvature. Given that all participants should be able to detect the change, given infinite time, the asymptote should be about 1.0. A greater parameter β indicates that participants are more likely to reach asymptote quickly: i.e. detect changes faster. The test-retest reliability ($N = 59$) of α was relatively low but significant, $r = 0.26$, $P = 0.044$, whereas the test-retest reliability of parameter β was moderate and significant, $r = 0.45$, $P < 0.001$. We used β to represent CB performance, as it most reliably reflects change detection over time both in terms of accuracy and RT. See Supplementary Materials for a more detailed description of data preparation.

Analyses

For tasks presented over two sessions (CB, CE, attentional capture, VSTM and perceptual rivalry tasks) measures were derived as the average from both sessions but for those who did not complete Session 2, only Session 1 data was used. The summary statistics, as well as the test-retest reliabilities of the measures are presented in Table 1. In terms of practice effects, paired t -tests between Session 1 and Session 2 data revealed that performance on most tasks significantly or marginally significantly improved on Session 2, although the effect sizes were small ($r < 0.3$); CE % correct, $t(59) = -2.65$, $P = 0.010$, $r = -0.23$; attentional capture, $t(59) = 3.06$, $P = 0.003$, $r = 0.21$; iconic VSTM, $t(59) = -4.00$, $P < 0.001$, $r = -0.18$, fragile VSTM, $t(59) = -3.73$, $P < 0.001$, $r = -0.18$; robust VSTM, $t(59) = -1.95$, $P = 0.057$, $r = -0.12$. The only exceptions were CB parameter β , $t(58) = 3.57$, $P = 0.001$, $r = 0.24$, with significantly poorer performance on Session 2, suggesting a more difficult stimulus set. For perceptual rivalry the number of perceptual alternations was significantly greater in Session 2 than in Session 1, $t(57) = -3.55$, $P = 0.001$, $r = -0.22$. We correlated performance across each task; a Pearson correlation matrix of CB task and other measures is available in Table 2 (for the full correlation matrix see Table 1.2 in the Supplementary Materials). We applied the false discovery rate (FDR) Benjamini-Hochberg procedure (Benjamini and Hochberg 1995) to correct for multiple comparisons. Out of the 14 correlations between CB task performance and other perceptual and cognitive measures, five significant correlations survived the correction. Two significant correlations did not survive; these are the correlations between CB task performance and perceptual rivalry, and robust VSTM accuracy. Scatterplots of the significant correlations between CB task performance and other measures can be seen in Figure 3.

Is change detection performance stable over time?

The test-retest reliabilities of all measures except the CE percentage correct were moderate to high (r ranged from 0.45 to 0.76). It must be noted that the change detection tasks were the only two tasks where different stimuli (e.g. different images of

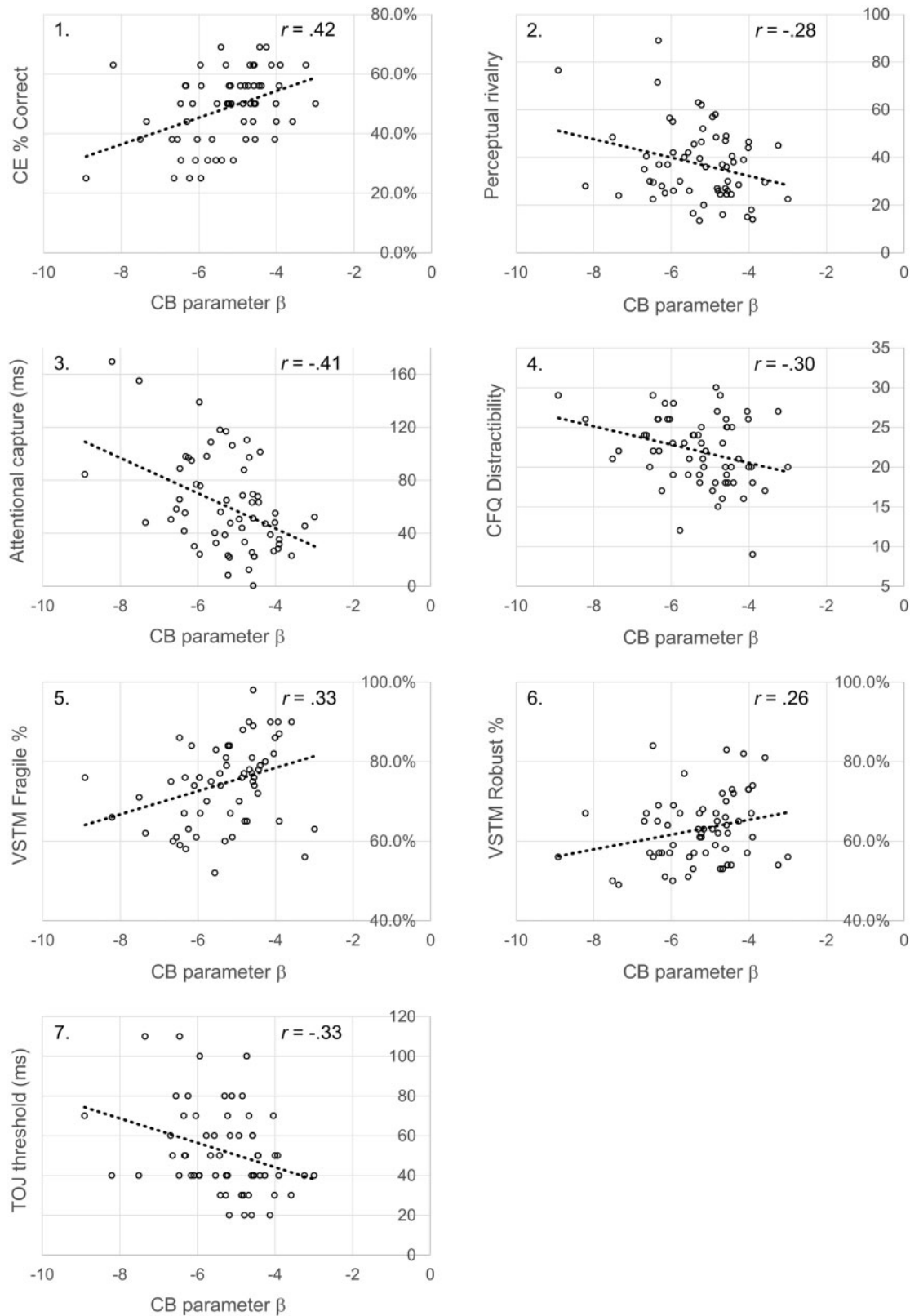


Figure 3. Scatterplots illustrating the significant correlations between CB parameter β and the other perceptual and cognitive measures: % of correctly identified changes in continuity error videos (1), number of alternations in perceptual rivalry (2), attentional capture (3), CFQ distractibility score (4), fragile VSTM accuracy (5), robust VSTM accuracy (6) and TOJ threshold (7).

Table 2. Pearson correlations among selected measures: CB parameter β ; % of correctly identified changes in continuity error videos, attentional capture is ms, iconic, fragile and robust VSTM % accuracy, number of alternations in perceptual rivalry, TOJ threshold in ms, CS parameters γ_{\max} , f_{\max} , β , and δ , CFQ distractibility score, VVIQ score and matrix reasoning task % accuracy, together with the associated significance values (2-tailed), lower and upper 95% bootstrapped confidence intervals and N, respectively

	CE % correct	Att. capture	VSTM Iconic	VSTM Fragile	VSTM Robust	Perceptual rivalry	TOJ	CS γ_{\max}	CS f_{\max}	CS β	CS δ	CFQ	VVIQ	Matrix
CB β														
<i>r</i>	0.42	-0.41	0.10	0.33	0.26	-0.28	-0.33	0.22	0.14	-0.15	0.03	-0.30	0.17	-0.05
<i>p</i>	0.001	0.001	0.420	0.009	0.041	0.030	0.008	0.116	0.319	0.292	0.809	0.017	0.184	0.726
Lower	0.16	-0.61	-0.18	0.08	-0.02	-0.52	-0.53	-0.03	-0.17	-0.48	-0.21	-0.51	-0.12	-0.29
Upper	0.63	-0.16	0.42	0.55	0.51	0.01	-0.13	0.45	0.40	0.17	0.26	-0.03	0.45	0.19
N	62	62	62	62	62	61	62	53	53	53	53	62	62	60

For the measures tested on two sessions values were averaged across both sessions. The significant correlations that survived correction for multiple comparisons are bolded.

Table 3. Exploratory factor analysis results for the 15 measures of perceptual and cognitive ability with varimax rotation (N = 52)

Measure	Rotated factor loadings	
	Visual stability	Visual ability
CB β	0.75	0.26
CE % correct	0.43	0.23
Attentional capture	-0.40	-0.09
VSTM Iconic	0.19	0.57
VSTM Fragile	0.46	0.65
VSTM Robust	0.48	0.28
Perceptual rivalry	-0.39	0.01
TOJ	-0.30	-0.52
CS γ_{\max}	-0.04	0.61
CS f_{\max}	0.08	0.19
CS β	-0.25	0.39
CS δ	0.12	-0.01
CFQ	-0.30	-0.18
VVIQ	0.28	-0.02
Matrix	-0.42	0.43

Loadings with the absolute value equal to or greater than 0.3 are bolded.

indoor scenes in the CB task and different video clips in the CE task) were presented in each of the two sessions. Therefore, it was anticipated that the test-retest reliabilities would be lower for the change detection tasks than for the other measures such as the VSTM task, where the stimuli were identical in both sessions. The CE task did not yield a significant test-retest reliability, presumably because of the very few trials (eight videos with continuity errors per session) and variability inherent in the format of the task.

What is the relationship between different change detection paradigms?

The CB parameter β was significantly positively related to CE percentage correct, $r = 0.42$, $P = 0.001$. The faster the detection rate in the CB task, the more continuity errors participants noticed in the video clips. This result suggests that the ability to notice visual changes is relatively stable over different stimulus sets (e.g. static naturalistic scenes, dynamic video clips). This finding indicates that change detection performance in the standard 'flicker' CB task can be generalized to more ecologically valid displays.

Do measures of visual short-term memory and attentional control predict change detection performance?

The CB parameter β task was significantly positively associated with accuracy of the later sub-divisions of VSTM, fragile VSTM, $r = 0.33$, $P = 0.009$, and robust VSTM, $r = 0.26$, $P = 0.041$, such that increased accuracy of these components of VSTM was associated with superior performance in the CB task (although the latter did not survive the FDR correction).

The CB parameter β was significantly negatively correlated with attentional capture, $r = -0.41$, $P = 0.001$. This suggests people with decreased tendency for attentional capture or superior ability to disengage from distracting stimuli were faster to detect visual changes in the CB task. CB parameter β was also significantly negatively associated with the distractibility component of the CFQ questionnaire, $r = -0.30$, $P = 0.017$, indicating that highly distractible people tend to notice visual changes more slowly.

Do measures of TOJ, CS and perceptual rivalry predict change detection?

The CB task performance correlated significantly with TOJ threshold, $r = -0.33$, $P = 0.008$, such that the participants who were capable of differentiating the temporal order of the onset of two stimuli closer in time were able to detect changes in the flickering scenes faster. This association was also found with the continuity error video task performance, $r = -0.26$, $P = 0.041$. However, none of the contrast sensitivity parameters were significantly associated with CB task performance.

The number of perceptual alternations in perceptual rivalry was significantly but negatively associated with CB parameter β , $r = -0.28$, $P = 0.030$. Faster alternation rate when viewing the ambiguous rotating sphere was associated with poorer change detection. This relationship suggests that the ability to form relatively stable visual predictions in light of conflicting incoming signals is associated with a superior change detection. However, it must be noted that this correlation did not survive correction for multiple comparisons.

Factor analysis

A principal axis factor analysis with a sample size of 52 participants was conducted on the 15 measures listed in Table 2 with orthogonal rotation (varimax). The Kaiser-Meyer-Olkin measure revealed that the sample was adequate [$KMO = 0.55$, higher than the acceptable standard of 0.5 (Hutcheson and Sofroniou

1999)]. Bartlett's test of sphericity was significant ($P < 0.001$), thus the hypothesis that the correlation matrix is an identity matrix was rejected. An initial factor analysis was run to identify the eigenvalues for each factor in the data and to analyse the scree plot. Six factors had eigenvalues over Kaiser's criterion (Kaiser 1958) of 1 and in combination explained 68% of variance. However, the scree plot showed an inflection point at the third factor; therefore, only two factors were retained and the analyses were re-run. The two retained factors explained 36% of the variance. Table 3 shows the factor loadings after rotation.

We term the first factor as 'visual stability' and interpret it as reflecting a high-level ability to form strong, robust visual representations and resist distraction. This is evidenced by the finding that accuracy of the later, more abstract sub-components of VSTM—fragile and robust—load highly and positively onto this factor, whereas iconic VSTM does not. In addition, this factor is associated with experiencing fewer alternations (i.e. greater perceptual stability) when viewing an ambiguous rivalry stimulus. The negative loading of attentional capture and self-reported distractibility further supports the interpretation that this factor represents stability of visual representations in face of distractors. Crucially, the factor loadings indicate that having strong, stable and accurate visual representations is associated with superior change detection ability, as both change detection tasks loaded highly and positively onto this factor. It must be noted that general intelligence loaded negatively onto this factor, indicating that visual stability and superior change detection cannot be explained simply by having a better executive function associated with intelligence.

We interpret the second factor, 'visual ability', as reflecting low-level perceptual sensitivity. This is suggested by the high loading of the iconic VSTM sub-component, which relies on lingering activity in the early visual system (Sligte et al. 2008, 2009). This factor also loaded on TOJ and on two parameters of contrast sensitivity (CS γ_{\max} and CS β). These CS parameters describe, respectively, the overall height (i.e. ability to detect over wide range of contrasts) and width (i.e. ability to detect over wide range of spatial frequencies) of the contrast sensitivity function. The negative loading of TOJ on this factor indicates that being able to identify the onset order of two stimuli when they occur close in time is associated with a higher latent capacity for visual sensitivity. However (and contrary to our initial predictions), the TOJ task cannot be construed as a 'pure' measure of visual sensitivity given that it also loads on the first factor and correlates significantly with CB. The TOJ task, like VSTM and CB, requires a comparison of visual signals over time and space. Similarly, the fragile VSTM loading on both factors suggests that performance on this STM sub-component is influenced by both sensitivity to signal and stability of representation. The high loading of general intelligence, as measured by matrix reasoning, on this visual ability factor is consistent with earlier research linking sensory discrimination and general intelligence (Deary 1986; Lindenberger and Baltes 1994; Anstey et al. 2002). Crucially, our measure of CB had a relatively low loading on this factor, which indicates that the mechanisms underlying change detection may not be directly related to perceptual sensitivity.

Discussion

We employed an individual differences approach to the study of CB in order to explore its neurocognitive basis in the visual hierarchy. After characterizing the variation, reliability and

generalizability of change detection performance, we examined its predictors from a battery of perceptual and cognitive tests. We interpret our findings within the framework of predictive processing, in which change detection depends on successful updating of visual predictions in light of new sensory evidence. More specifically, we examined whether CB performance is associated more strongly with the strength of perceptual predictions, or with sensitivity to sensory prediction errors. Our battery comprised 10 different perceptual and cognitive measures that were selected to target both high- and low-level mechanisms thought to be involved in change detection. Finally, we carried out an exploratory factor analysis in order to reveal the underlying structure of the performance on our battery of tests.

Our results revealed reliable individual differences in the ability to notice visual changes. Performance in both tasks of change detection, the CB task and the CE task, was significantly correlated, suggesting that detection in the CB paradigm using naturalistic scenes generalizes to more ecologically valid displays resembling everyday visual environments. There were several significant relationships between the variables that, for the most part, were in accordance with an association between strong visual representations and CB performance: higher fragile and robust VSTM accuracy, lower attentional capture, lower self-reported distractibility all predicted superior change detection. Perceptual rivalry alternation rate was negatively associated with CB performance, which suggests that perceptual stability may support the ability to detect changes. In addition, better TOJ performance also predicted superior change detection, which suggests sensitivity to temporal regularities may be important in change detection. No correlations were established between contrast sensitivity, general intelligence and change detection; likewise, vividness of visual imagery was not significantly correlated with CB.

The exploratory factor analysis revealed a two-factor solution. We identified the first factor as 'visual stability', which loaded strongly on both change detection tasks, fragile and robust VSTM accuracy, perceptual rivalry, attentional capture and self-reported distractibility. These factor loadings indicate that detection ability is associated with accuracy of the later sub-components of VSTM, with the ability to form relatively stable perceptual inferences in light of conflicting incoming signals (i.e. when viewing an ambiguous bistable stimulus), and with being able to resist attentional capture by task-irrelevant distractors both in a lab-based task and according to a self-reported distractibility measure. The psychophysical measures of iconic VSTM, TOJ threshold and contrast sensitivity loaded on a separate factor that we termed 'visual ability'. However, it is to be noted that these measures are not process-pure and individual differences on some tasks (e.g. TOJ and fragile VSTM) contributed to both factors. Nonetheless, the two-factor structure that emerged suggests change detection is better predicted by the strength and stability of visual predictions rather than by sensitivity to visual signal.

Among the correlations summarized above, the negative correlation between perceptual rivalry alternation rate and change detection ability is of particular interest. Some authors have proposed that a faster perceptual alternation rate is indicative of a visual system that assigns more weight to prediction error and consequently incorporates novel visual information into the predictions more readily (Hohwy et al. 2008; Kanai et al. 2011). Others have argued that it is unclear whether slow alternation rate in rivalry reflects strong, robust predictions or weak, noisy prediction errors (Sandberg et al. 2016); or conversely, whether a fast alternation rate reflects weak, unstable

predictions or strong, precise error signals (Megumi et al. 2015). Our results suggest that persistence of perceptual predictions may actually bestow a benefit for detecting unexpected visual changes, perhaps because it is easier to detect an inconsistency between a strong representation and sensory evidence that contradicts it. In contrast, if an individual generates vague, fleeting representations of a scene during the CB task, the appearance or disappearance of an object within the scene may not be consciously registered. This explanation is consistent with the finding that successful encoding of pre-change scene seems to be crucial for detecting a change (Tseng et al. 2010).

The loading of perceptual rivalry onto the 'visual stability' factor is also compatible with the well-established links between attentional control and percept dominance durations in bistable perception (Meng and Tong 2004; van Ee et al. 2005). In perceptual rivalry, selective attention has been shown to increase the dominance duration of the attended percept and delay the competing percept from entering awareness (van Ee et al. 2005). Eye-tracking studies reveal that when instructed to increase the dominance of particular percepts, participants fixate different regions of ambiguous stimuli (Van Dam and van Ee 2006). This, arguably, may prioritize certain information, which could be used to sustain a stable visual prediction. In our perceptual rivalry task, participants were instructed to fixate on a cross at the centre of the sphere and were not asked to influence its rotation voluntarily. However, individual differences in the ability to sustain endogenous attention could have affected the rate of perceptual alternation, as attention can be decoupled from fixation (Toppino 2003). It is conceivable that the factor structure of 'visual stability' reflects individual variation in how selective attention is allocated, given the high loadings on lab-based and self-report measures of the ability to resist distraction. For example, an increased ability to sustain selective attention could aid the stability of perceptual interpretation when viewing bistable stimuli.

We found that both lower attentional capture and self-reported distractibility were associated with superior change detection ability. This finding may reflect that people who are prone to attentional capture by task-irrelevant distractors have a high sensitivity to or poorer ability to disengage attention from visual transients such as the flicker in CB task, leading to relatively greater disruption in the ability to detect changes via exogenous shifts in attention. This interpretation is consistent with previous suggestions that CB results from impaired ability to detect changes via exogenous orienting due to the flicker (Beck et al. 2006) and that CB is overcome via engaging endogenous attention. In order to assess whether increased attentional capture correlates with reduced change detection ability even in contexts with no extremely salient masking visual transients, future research could investigate the relationship between attentional capture and gradual change detection (i.e. when one feature of an image changes very slowly and is not detected). Furthermore, there are types of change detection task where a tendency for greater attentional capture may confer a benefit. One example is the inattention blindness (IB) task in which participants engage in a primary task rather than actively search for a change, so that attentional capture by a salient unexpected stimulus is necessary to detect a change. There is some circumstantial evidence for this hypothesis, as adults with attentional deficit disorder tend to perform better than controls in IB paradigms (Grossman et al. 2015).

The association between the strength of VSTM and change detection was found in both types of change detection paradigm (CB task and CE task). Our study revealed that only certain sub-

components of VSTM relate to change detection performance; these are the fragile and robust VSTM. In contrast, the iconic VSTM component was related to perceptual sensitivity. Fragile VSTM loaded onto both factors, which may demonstrate that it represents an intermediate stage of VSTM, which relies on both perceptual sensitivity and memory-based processes. The finding that the later components of VSTM loaded onto the 'visual stability' factor comprising attentional capture and CFQ distractibility also supports the notion that working memory (WM) and attention are not distinct cognitive systems, but are intimately linked constructs which operate together in visual perception (Machizawa and Driver 2011). For example, attention is required in order to retrieve particular aspects of visual representations from WM (Awh and Jonides 2001). Furthermore, attention can be involuntarily captured by memory-matching distractor stimuli maintained in WM while engaging in visual search (Soto et al. 2005, 2008), and yet this influence can also be strategically overcome when the WM-maintained item is entirely task-irrelevant (Woodman and Luck 2007). In the CB task, poorer ability to disengage from irrelevant distractors (e.g. flicker) may limit the ability to access and integrate recently stored visual representations, which may slow down change detection. Alternatively, having weaker VSTM representations may limit the ability to suppress visual transients and to focus attention on task-relevant representations of the scene that are necessary for the integration of a change into the current percept.

Our findings motivate further research on the relationship between change detection and reliance on perceptual predictions versus sensory prediction errors. Perceptual rivalry has been discussed as one paradigm potentially revealing bias in predictive processing; however, the rivalry rate is also heavily influenced by eye movements and attentional control, which complicates interpretation. Therefore, other paradigms measuring the reliance on prior knowledge versus sensory evidence may be necessary. For example, Melloni et al. (2011) showed that the threshold for subjective visibility of degraded stimuli is lower for previously seen items than for novel items. In a similar vein, valid predictions have been found to accelerate the entry of visual stimuli into awareness in such paradigms as motion-induced blindness (Chang et al. 2015) and continuous flash suppression (Pinto et al. 2015), as well as to enhance perceptual metacognition (Sherman et al. 2015). A measure of individual differences in the visibility threshold of previously seen images, or the extent to which conscious access is accelerated by prediction, could provide an index of individual variability in the reliance on prior expectations in visual awareness, which could be correlated with change detection.

To conclude, we have shown that the ability to notice visual changes in naturalistic scenes is a relatively stable capacity that is generalizable to more ecologically valid CB paradigms. Our exploratory factor analysis suggests that individual differences in change detection are associated with the stability and strength of perceptual predictions to a greater degree than with visual sensitivity. The stability of perceptual rivalry, accuracy of late sub-components of VSTM and proneness to attentional capture and distractibility all formed a common factor that predicted detection ability, whereas the factor of 'visual ability,' formed mostly of measures reflecting sensitivity to contrast and timing of stimuli, did not load as strongly onto change detection. Robust visual predictions may enable the visual system to detect mismatches between the existing representation and the incoming signal more readily, perhaps via a more efficient top-down allocation of sustained endogenous attention in

accordance with current task goals, and/or a reduced tendency for exogenous attentional capture by task-irrelevant stimuli such as visual transients. A limitation of our study is that by being correlational in design it cannot assume any causality, only association. Therefore our results motivate further research to probe the neurocognitive mechanisms that underlie prioritization of predictions versus sensory evidence and how individual differences in predictive processing biases may relate to change detection, attention and visual awareness.

Supplementary data

Supplementary data is available at *NCONSC Journal* online

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